1 Introduction and short history of supercharging

Very likely, the future of the internal combustion engine can be described within the energy-sociopolitic environment as follows: For the foreseeable future, crude oil will still be the main energy source for internal combustion engines in automotive and other mobile applications; natural gas and, to a limited extent synthetic fuels (methanol and similar fuels), as well as, in the very long run, hydrogen, will additionally gain in importance. Internal combustion engines for these fuels are reciprocating or rotational piston combustion engines and gas and steam turbines. These engines are employed, under consideration of the particular requirements and according to their development status, in aircraft, locomotives, ships, stationary powerplants, and in road vehicles.

In aircraft design, the demand has always been for highest power density, i.e., smallest volume and highest power-to-weight ratio. The reciprocating piston internal combustion engine was the first power source to fulfill these requirements. With this, it actually enabled the engine-powered airplane and dominated this application until the end of the forties. Nowadays, with the exception of applications in small airplanes, it is superseded by the gas turbine, which as propeller turbine or as pure jet engine makes far higher power densities possible.

The classic power unit for train propulsion was the piston steam engine, which, in 2-, 3-, and 4-cylinder designs, lasted the longest for this use. Today, the steam locomotive is superseded by the electric or by the diesel locomotive, where diesel traction is more efficient for long hauls and stretches on which trains run infrequently. Diesel engines of high power density with hydraulic or electric power transfer today dominate diesel locomotive design. Repeatedly, the gas turbine was tested for this application – also as a short-time booster power unit – but could not prevail due to fuel economy and durability reasons.

In ship building, after the classic piston steam engine, first the steam turbine and then the gas turbine seemed to best accommodate the highly increasing power demands. In fast ships, also warships, where fuel consumption and fuel quality are not as decisive as power density and performance, the gas turbine even today occupies a niche market. But the highly supercharged, high-speed diesel engine, mostly in multiple engine configuration, is capturing this market to an increasing degree. In merchant shipping, due to its good fuel economy and the possibility to use even the cheapest heavy oils, the medium-speed and the slow-speed diesel heavy-oil engine have penetrated the market widely.

In large power plants with an output of 100 MW or more, the steam turbine still dominates. The extent to which smaller, decentralized electric power generating or heat and power cogeneration plants with internal combustion engines can take hold, remains to be seen. To cover peak power demands, the gas turbine has gained increased importance for this application.

For passenger cars as well as for trucks nowadays practically only the high-speed internal combustion engine is used, for reasons of its power density, durability, and cost, but especially for its ease of control and its flexibility in transient operation. Additionally, in the last decade extensive development work has led to reduced exhaust emissions with simultaneously improved efficiency. For truck engines, exhaust gas turbocharging in combination with charge air cooling has contributed decisively to attain both goals. From the heaviest truck down to transporters with about 4-tons payload, today practically only the exhaust gas turbocharged, charge air cooled, direct-injection diesel engine is used. In passenger cars as well, this engine configuration is gaining increased importance due to its extraordinary efficiency. In regard to supercharging, the passenger car gasoline engine remains problematical, due to its high exhaust gas temperature as well as to the requirement that an acceptable driving performance must be attained. This even more since also very narrow cost targets have to be met. But also here new approaches to technical solutions can be observed, so that it can be presumed that in 10 to 20 years supercharged combustion engines will totally dominate the market.

The history of supercharging the internal combustion engine reaches back to Gottlieb Daimler and Rudolf Diesel themselves.

Supercharging the high-speed gasoline engine is as old as it itself. Already Gottlieb Daimler had supercharged his first engines, as his patent DRP 34926 obtained in 1885 shows (Fig. 1.1). In this case, the piston's bottom was used, which in the four-stroke engine works as a mixture pump with double work-cycle frequency and therefore delivers a greater mixture volume than the work cylinder could aspirate.

Transferring the charge from the crankcase cavity into the work cylinder was performed by a valve in the piston bottom. The reason for Daimler's bold design was his desire for a possible speed and charge increase of the engines, despite the fact that at that time only very small intake and exhaust valves were feasible. The problems, especially with the piston bottom valve, however soon forced Daimler to abandon this intrinsically correct idea in favor of larger valves as well as the application of multiple-valve cylinder heads, which were designed by his co-worker Maybach.

Supercharging found its first series application in aircraft engines, especially to increase high-altitude performance. In the years from 1920 to 1940, turbo compressors were continuously improved, in aerodynamics as well as in the circumferential speed of the impellers.

Supercharging of gasoline engines experienced its first absolute peak in regard to power and high-altitude performance increases in aircraft engines during World War II. Brake mean effective pressure values of up to 23 bar were reached with mechanically powered turbo compressors. The last U.S. gasoline aircraft engines were the first series production compound engines, such as the 18-cylinder dual-radial compound engine from Curtiss Wright with a takeoff power of 2420 kW (see Fig. 6.22).

From about 1920, automotive supercharged engines for racing, but also for the short-term power increase of sport and luxury vehicles, were equipped with mechanically powered and engageable displacement compressors. In most cases they were one- or two-stage Roots blowers. Figure 1.2 shows such a passenger car engine with 40/60 hp from 2.6 liter displacement, built in 1921 by Daimler.

Exhaust gas turbocharged gasoline engines were first introduced into the U.S. market around 1960, e.g., the Chevrolet Corvair [76]. For the supercharging of gasoline engines, the big breakthrough towards large-scale series production, with the exception of use in airplanes, only happened very recently, with, e.g., the 2.3 liter compressor engine from DaimlerChrysler in its SLK and C class, or the exhaust gas turbocharged engines from Audi, Opel, and Saab.

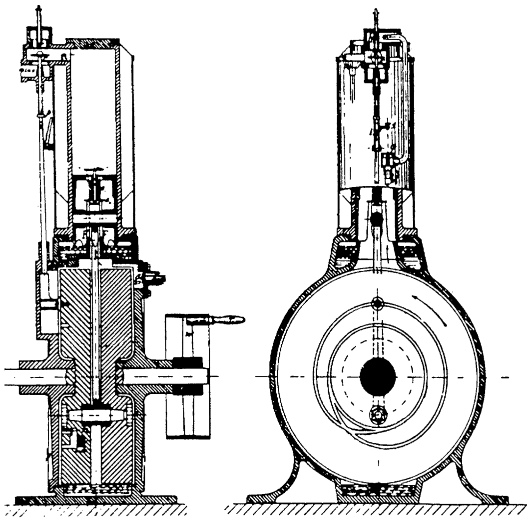

Fig. 1.1

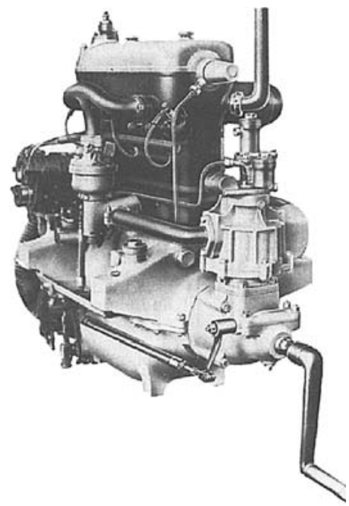

Fig. 1.2

Fig. 1.1. Patent DRP 34926 from 1885 for the high-speed gasoline engine, by Gottlieb Daimler

Fig. 1.2. 40/60 hp passenger car compressor engine with Roots blower from 1921, by Daimler

Rudolf Diesel also got involved with supercharging very early, as his patent DRP 95680 demonstrates (Fig. 1.3). In his cross-head engine he used the piston bottom as a two-stroke charge pump. This patent also describes a process for cooling the air in a downstream plenum.

With his layout, Diesel achieved a power increase of 30%. However, since he was primarily concerned about the efficiency of his engine and it dramatically deteriorated – due to a totally incorrect size of the intake valve and the downstream plenum, he stopped these tests. This type of

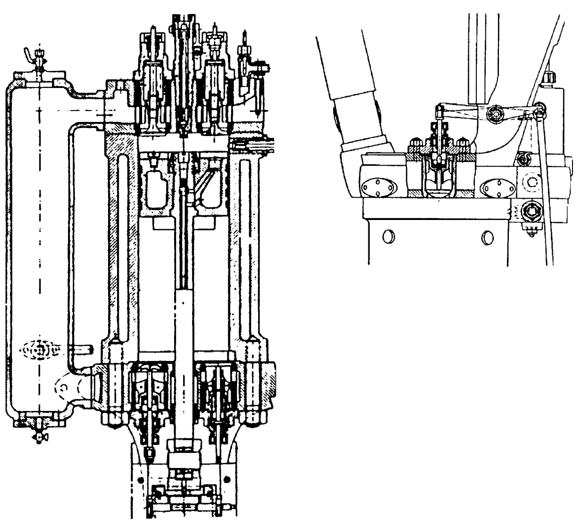

Fig. 1.3

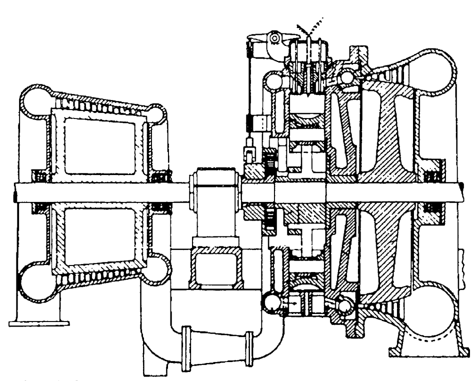

Fig. 1.4

Fig. 1.3. Patent DRP 95680 by Rudolf Diesel for a diesel engine with supercharging by the lower side of the piston

Fig. 1.4. Buechi's patent drawing DRP 204630 for a turbocompound diesel engine

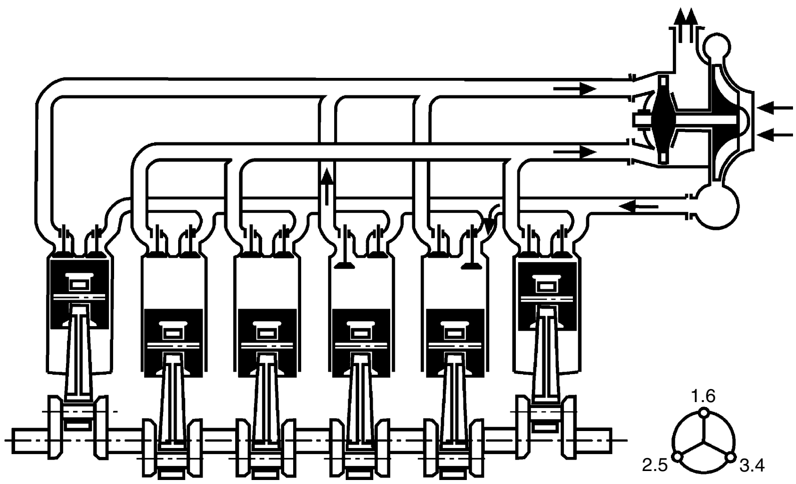

Fig. 1.5. Buechi's patent from 1925 for pressure-wave or pulse turbocharging via flow division

supercharging was, with correct dimensioning of the components, very successfully used 30 years later in marine diesel engines (e.g., by Werkspoor).

The development of exhaust gas turbocharging is closely connected with the name and patents of the Swiss engineer Alfred Buechi. As early as 1905, in patent DRP 204630 (Fig. 1.4) he described a turbocompound diesel engine – although not meaningful in the proposed form. But it still took until 1925 for the first exhaust gas turbocharged diesel engines to be introduced into the market, in the form of engines for two passenger ships and one stationary diesel engine from MAN and the Maschinenfabrik Winterthur. In both cases, the exhaust gas turbochargers were still located beside the engine. All chargers were designed by Buechi.

In the MAN marine engines, the mean effective pressure was increased by 40% to 11 bar, and important insights were gained:

Exhaust gas turbocharged engines are very overload capable.
The turbocharger group controls itself during operation.

In order to overcome the problem of a negative pressure gradient between charge pressure and exhaust gas backpressure, i.e., a negative scavenging gradient, which happened with these early exhaust gas turbochargers due to their low overall efficiency, in 1925 Buechi applied for another patent for a pressure-wave or pulse-charging layout. This was to be achieved by separating the exhaust manifolds and combining the cylinders with ignition intervals of more than 240° crank angle, as well as narrow exhaust manifold areas (Fig. 1.5).

The first tests at the Schweizer Lokomotiv- and Maschinenfabrik Winterthur on a 4- and a 6-cylinder engine with BBC charger were very promising. A power increase of 100% could be achieved with good thermodynamic results, and a third insight was gained:

Exhaust manifolds not only must have a small area but also must be as short as possible.

With that, flow and heat losses are minimized. Consequently, today exhaust gas turbochargers are mounted directly on the engine as a part of the exhaust manifold. Since then, the system described has been called Buechi-charging and is the basis for the exhaust gas turbocharging of all automotive engines.